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TRANSACTIONS.

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ON THE STRENGTH, ELASTICITY, DUCTILITY AND RESILIENCE OF MATERIALS OF MACHINE CONSTRUCTION,

AND ON VARIOUS HITHERTO UNOBSERVED PHENOMENA, NOTICED DURING EXPERIMENTAL
RESEARCHES WITH A NEW TESTING MACHINE, FITTED WITH AN AUTOGRAPHIC REGISTRY.

A paper by Prof. R. H. THURSTON, Member of the Society,

READ FEBRUARY 4, 1874.

SECTION I.

1. INTRODUCTORY.*—Some months ago, while engaged with the advanced classes of the Stevens Institute of Technology, in experimental investigations of the resistance of materials, it was found that coefficients were given, by various authorities, which neither accorded fully with each other or with those then obtained.

The desirability of determining how far these differences were due to errors of observation, and how far to variation in the quality of the materials examined, induced the writer to design several machines for the purpose of conducting with them a more extended and exact series of experiments. The machine for measuring torsional resistance was furnished with an automatic registry, recording a diagram which is a reliable and exact representation of all circumstances attending the distortion and fracture of the specimen. No system of personal observation could probably be devised which could yield results either as reliable or as precise as such a system of autographic registry, and, as no method previously in use had given simultaneously, and at every instant during the test, the intensity of the distorting force and the magnitude of the coincident distortion, it was anticipated that the new method of investigation

* *Vide* Journal Franklin Institute, 1873.

might be fruitful of new and, possibly, important results. This expectation, as will be seen, has been more than realized.

2. DESCRIPTION OF THE APPARATUS.—

The machine, as planned by the writer, and as built in the instrument makers' workshop, at the Stevens Institute, is shown in Fig. 1. This form is that with which the investigations to be described were made. Since its construction, in 1872, however, some changes and improvements have been made in the design to adapt it to general work, and new designs have been made for special kinds of work, as for wire mills, railroad shops and bridge building.

Two strong wrenches, CE , BD , are carried by the frames AA , A^1A^1 , and depend from axes which are both in the same line, but are not connected with each other. The arm, B , of one of these wrenches carries a weight, D , at its lower end. The other arm, C , is designed to be moved by hand, in the smaller machines, and by a gear and pinion, or a worm gear in larger forms of the apparatus. The heads of the wrenches are made as shown in Fig. 2, the recess, M , being fitted to take the head, on the end of the test pieces, which is usually given the form shown in Fig. 4.

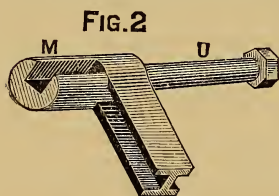
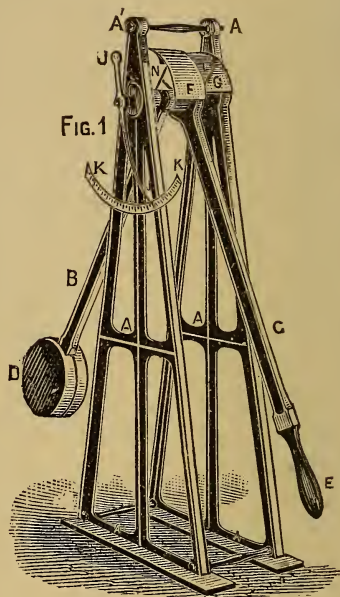


FIG. 3



A guide curve, F , of such form that its ordinates are precisely proportional to the torsional moments exerted by the weighted arm, BD , while moving up an arc to which the corresponding abscissas of the curve are proportional, is secured to the frame AA^1 . The pencil holder, J , is carried on this arm, BD , and as the latter is forced out of the vertical position, the pencil is pushed forward by the guide curve, its movement

being thus made proportionate to the force which, transmitted through the test piece, produces deflection of the weighted arm. This guide line is a curve of sines. The other arm, CE , carries the cylinder, G , upon which the paper receiving the record is clamped, and the pencil, J , makes its mark on the table thus provided. This table having a motion, relatively to the pencil, which is precisely the angular relative motion of the two extremities of the tested specimen, the curve described upon the paper is always of such form that the ordinate of any point measures the amount of the distorting force at a certain instant, while its abscissa measures the distortion produced at the same instant. The maximum hand, J , is sometimes useful as a check upon the record of maximum resistance.

The convenience of operation, the small cost,* and the portability of the machine are hardly less important to the engineer than the accuracy, and the extraordinary extent of information obtainable by it.

3. METHOD OF OPERATION.—The test piece having been given the shape and size which are found best suited for the purposes of the experiment, and to the capacity of the machine, it is placed in the jaws of the two wrenches, each of which takes one of its squared ends, and, a force being applied to the handle, E , the strain thrown upon the specimen is transmitted through it to the weighted arm, BD , causing it to swing about its axis until the weight exerts a moment of resistance which equilibrates the applied force. As the magnitude of the distorting force changes, the position of the weight simultaneously changes, and the pencil indicates, at each instant, the value of the stress upon the test-piece. As the piece yields under strains of increasing amount, also, the pencil is carried in the direction of the circumference of the cylinder on which its record is made, and to a distance which is proportional to the amount of distortion, *i.e.*, to the “total angle of torsion.” As the applied force increases, the specimen yields, and finally, rupture occurring, the pencil returns to the base line, at a distance from the starting point which measures the angle through which the test piece yielded before its fracture became complete.

4. INTERPRETATION OF THE DIAGRAMS.—It has been shown that the vertical scale of the diagrams produced is a scale of torsional moments, and that the horizontal scale is one of total angles of torsion. Since the resistance to shearing, in a homogeneous material, varies with the resist-

* Machines of the size of that used in these experiments, but of improved design, are made at the Stevens Institute, at prices as low as \$150.

ance to longitudinal stress, it follows that the vertical scale is also, for such materials, a scale of direct resistance, and that, with approximately homogeneous substances, this scale is approximately accurate, where, as here, all specimens compared are of the same dimensions. Since the elasticity of the material is measured by the ratio of the distorting force, to the degree of temporary distortion produced, the diagrams obtained will exhibit the elastic properties of the material, as well as measure its ductility and its resilience.

Referring to the diagrams shown in the accompanying plates, it will be noticed that the first portion of the line is a curve of small radius, convex toward the axis of abscissas, and that the line then rises at a slight inclination from the vertical, but becoming very nearly straight, until, at a point some distance above the origin, it takes a reversed curvature. The first portion of the line is probably formed by the yielding of the loosely fitted packing pieces securing the heads of the specimen, and, after they have taken a bearing, by the early yielding, in some materials, of particles already overstrained. When a firm hold is obtained, the line becomes sometimes nearly straight, and the amount of distortion is seen to be approximately proportional to the distorting force, illustrating "Hooke's law," *Ut tensis sic vis*.

After a degree of distortion which is determined by the specific character of each piece, the line becomes curved, the change of form having a rate of increase which varies more rapidly than the applied force. When this change commences, it seems probable that the molecules, which, up to that point, retain generally, their original distribution, while varying their relative distances, begin to change their positions with respect to each other, moving upon each other in a manner similar, probably, to that action described by Mon. Tresca, and called the "Flow of Solids,"* and to which attention has already been called by Prof. J. Thompson.†

It is this point, at which the line commences to become concave toward the base, that is considered to mark the "limit of elasticity." It will be noticed that it is well defined in experiments upon woods, is less marked, but still well defined in the "fibrous" irons and the less homogeneous specimens of other metals, and becomes quite indeterminate with the most homogeneous materials, as with the best qualities of well worked cast-steel. This point does not indicate the first "set,"

* L'Ecoulement des Corps Solides; Paris, 1869, 1871.

† Cambridge and Dublin Mathematical Journal, Vol. III, 1848, pp. 252-266.

since, as will be hereafter seen, a set is found to occur, either temporary or permanent, and usually partly temporary and partly permanent, with every degree of distortion, however small. It is at this "elastic limit" that the sets begin to become considerable in amount and almost wholly permanent.

The inclination of the straight portion of the line from the vertical measures the *stiffness* of the specimen, the quantity $\text{Cot. } \Theta = \frac{1}{\tan. \Theta}$ being the ratio of the distorting force to the amount of distortion up to the "limit of elasticity." As it would seem from the results of experiment, as well as of deduction, that this rigidity is very closely, if not precisely, proportional to the hardness, in homogeneous substances, this quantity $\text{Cot. } \Theta$ may be taken, for practical purposes, as a measure of the hardness of the metals, as well as of their elastic resistance to compression.

After passing the elastic limit, the line becomes more and more nearly parallel to the base line, and then, with the woods invariably, and in some cases with the metals, begins to fall rapidly before fracture becomes evident in the specimen. Where the rising portion of the line turns and becomes nearly parallel with the axis of abscissas, the viscosity of the material is such that the outer particles "flow" upon those within, and, while themselves still offering maximum resistance, permit molecules nearer the axis to also resist with approximately maximum force. It seems probable that, with the more ductile substances, nearly all are brought up to a maximum in resistance before fracture occurs, and this circumstance will be seen hereafter to have an important influence in determining the resistance to rupture. The hardest and most brittle materials break, with a snap, before any such flow becomes perceivable, and before the line of the diagram commences to deviate, in the slightest degree, from the direction taken at the beginning, and before the approach to the elastic limit is indicated. It is evident that the standard formulas for torsional, as well as for other forms of resistance, cannot be perfectly correct, since they do not exhibit this difference in the character of the resistance offered by ductile and by rigid materials.

The *elasticity* of the material is determined by relaxing the distorting force, at intervals, and allowing the specimen to relieve itself from distortion so far as its elasticity will permit. In such cases, the pencil will be found to have traced a line resembling, in its general form and position, in respect to the coördinates, that forming the initial portion of the diagram, but almost absolutely straight, and more nearly vertical.

The degree of inclination of this line indicated the elasticity, precisely as the initial straight line was made to give a measure of the original stiffness of the test piece, the cotangent of the angle made with the vertical,

$$\text{Cot. } \Phi = \frac{1}{\text{Tan. } \Phi}$$

being the ratio of the force required to spring the piece through the range recoverable by elasticity, to the magnitude of that range. The fact, to be shown, that this value is always greater than *Cot. Θ* , for the same metal is evidence that more or less permanent set will always occur, and that the original stiffness of the specimen is always modified, whatever the magnitude of the applied force. The form of the line of elastic change indicates also the character of the molecular action producing it.

Finally, the form of the curve after passing the maximum, or after passing the point at which fracture commences, exhibits the method of variation of strength during the process of fracture. This portion is very difficult to obtain, with even approximate accuracy, with any but the toughest and most ductile materials. This terminal portion of the diagram would be, theoretically, a cubic parabola, the loss of resisting power varying with the progressive rupture of concentric layers, and the remaining unbroken cylindrical portion becoming smaller and smaller until resistance vanishes with the fracture of the axial line. In some cases, the curves obtained from ductile metals exhibit this parabolic line very distinctly. In all hard materials, the jar produced by the sudden rupture of surface particles is sufficient to separate those within, and the terminal line is straight and vertical.

The *homogeneity* of the material tested is frequently hardly less important than its strength, and it is very desirable to obtain evidence which may enable the experimenter to determine the value of tests of samples as indicative of the character of the lot from which the specimens may have been taken. If the specimens are found to be perfectly homogeneous, it may be assumed with confidence that they represent accurately the whole lot. If the samples are irregular in structure and in strength, no reliable judgment of the value of the lot can be based upon their character, and there can be no assurance that, among the pieces accepted, there may not be untrustworthy material which may possibly be placed just where it is most important to have the best. It is evident that the more homogeneous a material, the more regularly would changes in its resistance take place, and the smoother and more symmetrical would be the diagram. The depression of the line immediately after

passing the elastic limit exhibits the greater or less homogeneousness of the material. The fact is illustrated in a striking manner in some of the curves presented, and we thus have—what had never, I believe, been before found—this method of determining homogeneousness.

The *resilience* of the specimen is measured by the area included within its curve, this being the product of the mean force exerted into the distance through which it acts in producing rupture, *i.e.*, it is proportional to the work done by the test piece in resisting fracture, and represents the value of the material for resisting shock. The area taken within the ordinate of the limit of elasticity, measures the capacity for resisting shock without serious distortion or injurious set.

The *ductility* of the specimen is deduced from the value of the total angle of torsion, and the measure is the elongation of a line of surface particles, originally parallel to the axis, which line assumes a helical form as the test piece yields, and finally parts at or near the point where the maximum resistance is formed. Its value is given on Plates II and III for each ten degrees of arc. Since, in this case, there is no appreciable reduction of section, or change of form, in the specimen, this value of elongation is our actual measure of the maximum ductility of the material, and is an even more accurate indication than the area of fractured cross section as usually measured after rupture by tension. It is to be understood that wherever comparisons are here made, without the express statement of other conditions, that specimens of the same dimensions are always represented in the diagrams.

5. DESCRIPTION OF ILLUSTRATED DIAGRAMS. THE WOODS.—Plates I and II exhibit sets of curves which illustrate the general characteristics of a large number of materials, the first showing the peculiarities noted during experiments on the woods, and the second giving an interesting comparison of the metals.

The woods experimented upon were the following, the numbers of the respective curves on Plate I, indicating the material here correspondingly marked :—

1. White pine (*Pinus Strobus*).
2. Southern pine (*Pinus Australis*), sap wood.
3. Southern pine, heartwood.
4. Black spruce (*Abies Nigra*).
5. Ash (*Fraxinus Americannus*).
6. Black walnut (*Juglans Nigra*).
7. Red cedar (*Juniperus Virginianus*).

8. Spanish mahogany (*Swietenia Mahogani*).
9. White oak (*Quercus Alba*).
10. Hickory (*Carya Alba*).
11. Locust (*Robinia Pseudo-acacia*).
12. Chestnut (*Castanea Vesca*).

The specimens were all of the form shown in Fig. 3, three and three-fourths inches long, with a diameter of neck of seven-eighths of an inch.

It will be noticed that, in all cases, at the commencement of the line, it rises, at a slight inclination from the vertical, and almost perfectly straight. This confirmation of Hooke's law, within the limit of elasticity, is best shown in the detached portion *a, a, a*, of the curve obtained with locust, in which the horizontal scale is somewhat magnified. The distortion is seen to be very precisely proportional to the distorting force, until the law changes at the limit of elasticity.

It will be observed that, in the larger number of cases, the torsional resistance increases with great regularity nearly to the angle of maximum stress where, suddenly, this rapid rate of increase ceases, and the limit of elastic resistance being passed, resistance diminishes rapidly with further increase of angular movement, until it becomes zero. In the tougher and more dense varieties, this decrease of resistance occurs less slowly, and in some cases only disappears after a large angle of torsion is recorded. In the curves of exceptionally strong and tough woods, in which there is known to exist a great excess of longitudinal over lateral cohesion, as in those of black walnut 6, 6, locust 11, 11, and especially in those of hickory 10, 10, a peculiarity is perceivable which is somewhat remarkable, and which is especially important in a connection to be hereafter referred to at length.

In these instances the resistance is proportional to the amount of torsion, until a maximum is reached, the line then falls as torsion continues, until a minimum is passed, the curve then again rising and passing another maximum before finally commencing an unintermitted descent to the axis of abscissas. Where the difference between longitudinal and lateral cohesion is exceptionally great, the second maximum may, as illustrated, for example, by the line described in recording the test of hickory, have a higher value even than the first. This interesting and previously unanticipated peculiarity was shown, by careful observation, to be due to the sudden yielding of lateral cohesion when the torsional moment reached the value indicated by the first minimum.

The fibres being thus loosened from each other, this loose bundle of filaments yielded readily, until, by lateral crowding as they assumed a helical form and enwrapped each other, their slipping upon each other was gradually checked, and resistance again commenced increasing.

At the second maximum, yielding again began in consequence of the breaking of fibres under the longitudinal stress measured by that component of torsional force having a direction parallel with the filaments in their new positions, the exterior surface threads parting first under this tensile stress, and rupture progressing by the yielding of layer after layer, until the axial line being reached, resistance vanished. In this case, rupture seems never to occur by true shearing along one defined transverse plane. This feature of depression in the curve, occurring as described, is therefore the indication of a lack of symmetry in the distribution of resisting forces. It is evident that it may occur either by a difference in the value of cohesive force in the lateral and longitudinal directions, or by the structural defects of a specimen in which the substance itself may be endowed with cohesion of equal intensity in all directions.

The curves shown in Plate I exhibit well the relative values of these materials for the various purposes of the engineer.

White pine, 1, 1, 1, is shown by the considerable inclination of the line of stiffness from the vertical, to be soft and deficient in rigidity. The limit of elasticity is quickly reached, and the maximum resistance of the specimen is found at $15\frac{1}{2}$ foot-pounds of moment. Rapidly losing strength after passing the limit of resistance, it is entirely broken off at an angle of 130° . The small area comprised by the diagram proves its deficiency of resistance, and its inability to sustain shock.

Yellow pine, 2, 2, 2, 3, 3, 3, far excels the first in all valuable properties shown by the curve. The sapwood seems, in the specimens tested, equally stiff with the heart, but it reaches the elastic limit sooner. The general form of the diagram is the same in both, and is characteristically different from that of the white pine. It evidently has great value wherever rigidity, strength, toughness and resilience are desired in combination with lightness, the latter most important quality, together with their cheapness, aiding the qualities here shown in determining the application of these woods so extensively for general purposes. It should be noted that, since all comparisons of strength are based on measures of volume, a comparison of densities should usually be obtained to assist the judgment in making a choice from among materials of which tests have been made.

Spruce, 4, 4, 4, while possessing far less stiffness than even white pine, excels it somewhat in strength, passing its maximum at 18 foot-pounds, and submitting to a torsion of nearly 200° . It is proven to possess, proportionally greater resilience also. It is, however, far inferior to the yellow pine in every respect.

Ash, 5, 5, 5, is more deficient in strength and toughness than is generally supposed, and rapidly loses its power of resistance after passing the maximum, which point is found at about $27\frac{1}{2}$ foot-pounds. These specimens may have been of exceptionally poor quality, or, possibly, were over-seasoned.

Black walnut, 6, 6, 6, is remarkably stiff, strong and resilient, its diagram resembling somewhat that of oak in general form and dimensions. The maximum of resistance reaches 35 foot-pounds, and the most ductile specimen was only broken off after yielding through an arc of 220° . Its stiffness is shown by the fact that it required a moment of 25 foot-pounds to spring it 10° , yellow pine requiring but 22 foot-pounds and spruce but 8, to give them the same amount of distortion.

Red cedar, 7, 7, 7, is very stiff, but is brittle and deficient in strength, breaking off at 92° , and having a maximum power of resistance of but $20\frac{1}{2}$ foot-pounds. It is, however, one of the stiffest of the woods, its specimen requiring 20 foot-pounds of torsional moment to produce a total angle of torsion of but 5° .

Spanish mahogany, 8, 8, 8, is both strong and stiff, bearing a stress of 44 foot-pounds, and requiring 32 to produce torsion of 10° .

White oak, 9, 9, 9, exhibits less strength than either good mahogany, locust or hickory, but it is exceedingly tough and resilient. Passing the maximum at an angle of 15° , under a torsional stress of $35\frac{1}{2}$ foot-pounds, it retains its power of resistance nearly unimpaired up to about 70° , and then slowly yields until it suddenly gives way, after passing the angle 250° , under a strain due to 9 foot-pounds, and breaks off completely at 253° . This strength, toughness and endurance, under strains due to impact, may be attributed to its considerable lateral cohesion, and to the interlacing of its tenacious fibres, which gives this wood its "cross" grain.

Hickory, 10, 10, 10, has the highest maximum found during these experiments, the second of the pair of maxima already referred to being considerably above the maximum of locust even. This specimen exhibits well the well-known valuable properties of the material, requiring 45 foot-pounds to twist it 10° , reaching a limit of elasticity at 54 foot-

pounds and 13°, and having a maximum resisting moment of 50½ foot-pounds. When it finally yields, it does so quite rapidly, breaking off at 145°.

Locust, 11, 11, 11, gives an excellent diagram. It is the stiffest of all, yielding but 10° at its maximum of 55 foot-pounds, and one piece, which was unusually hard and compact, requiring 48 foot-pounds to distort it 4°, and reaching a maximum angle of torsion of nearly 160°.

It was noticed, during this series of experiments, that different specimens of the same species of wood usually exhibited very nearly equal strength and rigidity, and that marked differences were only occasionally noted in elasticity and resilience.

6. THE METALS, AND THE CURVES PRODUCED BY THEM.—Plate II exhibits a series of curves which illustrate well the general characteristics and the peculiarities of representative specimens of the principal varieties of useful metals. In some cases two specimens have been chosen for illustration, of which one presents the average quality, while the other is the best and most characteristic of its class.

The diagrams obtained by testing metals are quite different in general character from those registered in experiments on the woods, yet there are some points of resemblance which it will be instructive to notice, since these similar characteristics indicate similar properties of the two materials, and a comparison aids greatly in the interpretation of the diagrams. The woods have a structure which differs, in a distinguishing degree, both in the distribution of the substance and in the action of those molecular forces capable of resisting rupture, from that of the metals, the latter being far more homogeneous, in both respects, than the former. Wood consists of an aggregation of strong fibres, lying parallel, or approximately so, and held together often by a comparatively feeble force of lateral cohesion. The latter force being, as often happens, destroyed, the mass becomes a collection of loose threads having the general character of a rope or cord, with slight or no twist. The metals, on the other hand, are naturally homogeneous, both in structure and in the distribution and intensity of the molecular forces. Well-worked and thoroughly annealed cast-steel, as an example, is equally strong in all directions, is perfectly uniform in its structural character, and is almost absolutely homogeneous as to strain. It would be expected, therefore, that the diagrams obtained by breaking such a material would differ from those of the woods, in having a smoother and more regular form, and this is shown to be actually the case by observation of the curves of

cast-steel, cast-iron, bronze and others of the more homogeneous metals and alloys.

Some of the metals, it will be noticed, yield diagrams of less regular form. Wrought-iron, as usually made, has a somewhat fibrous structure, which is produced by particles of cinder, originally left in the mass by the imperfect work of the puddler while forming the ball of sponge in his furnace, and which, not having been removed by the squeezers or by hammering the puddle ball, are, by the subsequent process of rolling, drawn out into long lines of non-cohering matter, and produce an effect upon the mass of metal which makes its behavior, under stress, somewhat similar to that of the stronger and more thready kinds of wood. In the low steels, also, in which, in consequence of the deficiency of manganese accompanying, almost of necessity, their low proportion of carbon, this fibrous structure is produced by cells and "bubble holes" in the ingot, refusing to weld up in working, and drawing out into long microscopic, or less than microscopic, capillary openings.

In consequence of this structure we find, as we should have anticipated, a depression interrupting the regularity of their curves, immediately after passing the limit of elasticity, precisely as the same indication of the *lack of homogeneousness of structure* was seen in the diagrams produced by locust and hickory.

The presence of internal strain constitutes an essential peculiarity of the metals which distinguishes them from organic materials. The latter are built up by the action of molecular forces, and their particles assume naturally, and probably invariably, positions of equilibrium as to strain. The same is true of naturally formed organic substances. The metals, however, are given form by external and artificially produced forces. Their molecules are compelled to assume certain relative positions, and those positions may be those of equilibrium, or they may be such as to strain the cohesive forces to the very limit of their reach. It even frequently happens, in large masses, that these internal strains actually result in rupture of portions of the material at various points, while in other places the particles are either strongly compressed, or are on the verge of complete separation by tension. This peculiar condition must evidently be of serious importance, where the metal is brittle, as is illustrated by the behavior of cast-iron, and particularly in ordnance. Even in ductile metals it must evidently produce a reduction in the power of the material to resist external forces. This condition of internal strain may be relieved by annealing hammered and rolled metals, and by cooling cast-

ings very slowly, in order that the particles may assume, naturally, positions of equilibrium. In tough and ductile metals, internal strain may be removed by heating to a high temperature and then cooling under the action of a force approximately equal to the elastic resistance of the substance. This process, called "Thermo-tension," was first used by Professor Johnson in the course of his experiments as a member of a Committee of the Franklin Institute, in 1836,* and the effect of this action in apparently strengthening the bars so treated, was stated in the report of the committee. The fact that this effect was very different with different kinds of iron was also noted, but it does not appear that the cause of this, which they term "an anomalous" condition of the metal was discovered by them.

Metals which are very ductile may frequently be relieved of internal strain, also, by simply straining them while cold to the elastic limit, and thus dragging all their particles into extreme positions of tension, from which, when released from strain, they may all spring back into their natural and unstrained positions of equilibrium. This fact, which does not seem to have been previously discovered by investigators of this subject, will be seen to have an important bearing upon the resisting power of materials, and upon the character of all formulas in which it may be attempted to embody accurately the law of resistance of such materials to distorting or breaking strain.

Since straining the piece to the limit of elasticity brings all particles subject to this internal strain into a similar condition, as to strain, with adjacent particles, it is evident that indications of the existence of internal strain, and through such indications a knowledge of the value of the specimen, as affected by this condition, must be sought in the diagram, before the sharp change of direction which usually marks the position of the limit of elasticity is reached. As already seen, the initial portion of the diagram, when the material is free from internal strain, is a straight line up to the limit of elasticity. A careful observation of the tests of materials of various qualities, while under test, has shown that, as would, from considerations to be stated more fully hereafter, in treating of the theory of rupture, be expected, this line, *with strained materials, becomes convex towards the base line*, and the form of the curve, as will be shown, is parabolic. The initial portion of the diagram, therefore, determines readily whether the material tested has been subjected

* Journal Franklin Institute, 1836--7.

to internal strain, or whether it is homogeneous as to strain. This is exhibited by the *direction* of this part of the line as well as by its form. The existence of internal strain causes a loss of stiffness, which is shown by the deviation of this part of the line from the vertical to a degree which becomes observable by comparing its inclination with that of the line of elastic resistance, obtained by relaxing the distorting force—*i.e.*, the difference in inclination of the initial line of the diagram and the lines of elastic resistance, *e, e, e*, indicates the amount of existing internal strains.

7. FORGED IRON.—In Plate II, the curves numbered 6, 1, 22 and 100, are the diagrams produced by three characteristic grades of wrought-iron. The first is a quality of English iron, well known in our market as a superior metal. The second is one of the finest known brands of American iron, and the third is also of American make, but it does not usually come into the market in competition with well known irons, in consequence of the high price which is consequent upon the necessary employment of an unusual amount of labor, in securing its extraordinarily high character.

No. 6 at first yields rapidly under moderate force, only about 50 foot-pounds of torsional moment being required to twist it 5°. It then rapidly becomes more rigid, as the internal strains, so plainly indicated, are lost in this change of form, and at 6° of torsion, the resistance becomes 60 foot-pounds, as measured at *a*. Here the elastic limit is reached. The next 3° produce no increase of resistance. This fact shows that this iron, which was not homogeneous as to strain, is also not homogeneous in structure. We conclude that it must be badly worked and seamy, and that it may have been rolled too cold; the former is the probable reason of its lack of homogeneous structure, the latter gave it its condition of internal strain. After the first 9° of torsion, resistance steadily rises to a maximum, which is reached only when just on the point of rupture, and the piece finally commences breaking at 250°, and is entirely broken off at 285°. Its maximum elongation, whose value is proportionable to the reduction of section noted with the standard testing machines, is 0.691. The terminal portion of the line, after rupture commences, is not usually accurate as a measure of the relation of the force to the distortion. The increase of resistance between the angle 9° and the angle of rupture is produced by the additional effort in resistance due to the “flow” or drawing out of particles, as already indicated, and the precise effect of

which will be noticed at length in a succeeding section relating to the theory of rupture.

Applying the scale for tension, which in the case of these curves was very exactly 24,000 pounds per square inch for each inch measured vertically on the diagram, we find that the elastic limit was passed under a stress equivalent to a tension of 19,800 pounds per square inch, and that the ultimate tenacity was 59,200 pounds per square inch. When nearly at the maximum the specimen was relieved from stress, the pencil descending to the base line, and the elasticity of the piece produced a certain amount of recoil. The angle intercepted between the foot of this nearly vertical line, *c*, and the origin at *o*, measures the *set*, which is almost entirely permanent. The distance measured from the foot of the perpendicular, let fall upon the axis of abscissas, from the head of this line to the foot of the line *e*, measures the elasticity, *and is inversely proportional to the modulus*. A comparison of the inclination of the line made by the pencil in reascending, on the renewal of the strain with the initial line of the diagram, gives the indication of the amount of internal strain originally existing in the piece.

It will be noticed that the horizontal movement of the pencil is recommenced at *I*, under a higher resistance than was recorded before the elastic line was formed. In this case the piece had been left under strain for some time before the stress was relieved, and the peculiarity noted is an example of an increase of resistance under stress,* or more properly of the *elevation of the elastic limit*, of which more marked examples will be shown subsequently.

The exceptional stiffness and limited elastic range here shown, as compared with the other examples given, is probably a phenomenon accompanying and due to this increase of resistance under stress.

Examining No. 1 in a similar manner, we find that it is far freer from internal strain than No. 6, its initial line being much more nearly straight and rising more rapidly. It is rather less homogeneous in structure, and is forced through an arc of 6° , after having passed its elastic limit, before it begins to offer an increasing resistance. It is evidently a better iron, but less well worked, and, as shown by the position of the elastic limit, is somewhat harder and stiffer. No. 1 retains its higher resistance quite up to the point at which No. 6 received its incidental accession of resistance by standing under strain, and the two pieces break at, practically, the same point, No. 1 having slightly the

* *Vide* Transactions, Vol. II, page 290.

greater ductility. When the "elastic line," e , is formed, just before fracture, it is seen that No. 1 has a greater elastic range and a lower modulus than No. 5. It should be observed that the line by which the pencil *descends* to the base line has usually no value, owing to the fact that no care is generally taken to remove the stress as gradually as it is applied. When such care is taken, the lines are usually coincident, and do not form the loop here seen. It will also be noticed that these lines often cross each other, that on the right being the important line. The elastic line formed by No. 1 at between 40° and 45° of torsion is seen to be very nearly parallel with that obtained near the terminal portion of the diagram, and illustrates the fact here first revealed to the eye, that *the elasticity of the specimen remains practically unchanged up to the point of incipient rupture*, and this fact corroborates the deductions of Wertheim* and others who came to this conclusion from less satisfactory modes of research. All experiments yet made give a similar result.


No. 22 illustrates the characteristics of a metal which probably represents one of the best qualities of wrought iron made in this or in any other country, and with which every precaution has been taken to secure the greatest possible perfection, both in the raw material and in its manufacture. The fact that it finds a market at sixteen cents a pound proves that even such care and expense are well applied. The line of this diagram, starting from O , rising with hardly perceptible variation from its general direction, turns, at the elastic limit, a , under a moment of about 80 foot-pounds, equivalent to a tension of about 24,000 pounds per square inch; and with between 2° and 3° of torsion only, and thence continues rising in a curve almost as smooth and regular as if it had been constructed by a skilful draughtsman. Reaching a maximum of resistance to torsion of 220 foot-pounds and an equivalent tensile resistance of over 66,000 pounds per square inch, at an angle of 345° , it retains this high resistance up to the point of rupture some 358° from its starting point. The maximum elongation of its exterior fibres is 1.2, making them at rupture 2.2 times their original length. This would produce a probable breaking section in the common testing machine equal to 0.4545 of the original section.†

From the beginning to the end this specimen exhibits its superiority, in all respects, over the less carefully made irons, Nos. 1 and 6, which, it should be remembered, are themselves deservedly known as good brands,

* *Vide Annals de Chimie et de Physique.*

† Compare Kirkaldy; *Strength of Iron and Steel*; pp. 111, 135, for reduction in Yorkshire and Swedish bars. The elongation there given has, of course, no value as a measure of ductility.

The homogeneity of No. 22 is almost perfect, both in regard to strain and to structure, the former being indicated by the straightness of the first part of the diagram and its parallelism with the "elastic line," e , produced at $217\frac{1}{2}^\circ$, and the latter being proven by the beautiful accuracy with which the curve follows the parabolic path indicated by our theory as that which should be produced by a ductile homogeneous material. At similar angles of torsion, No. 22 offers invariably much higher resistance than either Nos. 1 or 6, and this superiority, uniting with its much greater ductility, indicates an immensely greater resilience. It is evident that for many cases, where lightness combined with capacity to carry live loads and to resist heavy shocks are the essential requisites, this iron would be by far preferable, notwithstanding the cost of its manufacture, to any of the cheaper grades. Comparing their elasticities, as shown at 210° , 215° , it is seen that No. 22 is about equally stiff and elastic with No. 1, while both have a wider elastic range and are less rigid, and hence are softer than No. 6, whose elastic line is seen at 221° . All of the characteristics here noted can be accurately gauged by measuring the diagrams, and constants are readily obtained for all formulas, as illustrated in a later section of this paper, in which the construction of formulas and the determination of constants will be made the subject of investigation.

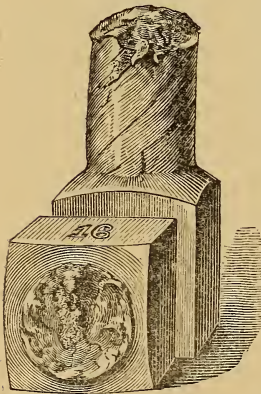
No. 100 is the curve obtained from a piece of Swedish iron, marked . Its characteristics are so well marked that one familiar with the metal would hardly fail to select this curve from among those of other irons. Its softness and its homogeneous structure are its peculiarities. Its curve, at first, coincides perfectly with that of No. 6. It has, however, slightly less of the condition of internal strain, and a somewhat higher limit of elasticity. The elastic limit is found at $5\frac{1}{2}^\circ$ of torsion, and at a stress of 65 foot-pounds of moment, equivalent to 19,500 pounds on the square inch, in tension. Its increase of resistance, as successive layers are brought to their maximum and begin to flow, is very nearly the same as that of the specimens Nos. 1 and 6, and the line lies between the diagrams given by these irons up to 30° , and then falls slightly below the latter. At 220° , it attains a maximum resisting power, and here the outer surface begins to rupture, after an ultimate stretch, of lines formerly parallel to the axis, amounting to 0.564. Had this elongation taken place in the direction of strain, as in the usual form of testing machine, it would have produced a reduction of section to 0.64, the original area.* At this

*Compare Styffe; Strength of Iron and Steel; p. 133, Nos. 26-30.

point the stress in tension equivalent to the 176 foot-pounds of torsional stress, is 52,800 pounds per square inch. From 250° the loss of resistance takes place rapidly, but the actual breaking off of the specimen did not occur until it had been given a complete revolution. This part of the diagram distinguishes the metal from all others, and shows distinctly the exceptionally tough, ductile and homogeneous character which gives the Swedish irons their superiority in steel making. No. 22, even, although much more more extensible, is harder than No. 100, and yields more suddenly when it finally gives way.

A comparison of the results here recorded with those obtained by Styffe,* will afford a good basis upon which to form an idea of the accuracy as well as the convenience of this method of deriving them. An examination of the broken test piece gives some evidence confirmatory of the record. The exterior surface of the twisted portion has an appearance intermediate between that of No. 1, Fig. 5,† and No. 22, Fig. 7, with an evident tendency to “kink.” The surface of fracture is lighter and more lead-like than even No. 22, and its “fibre” is finer and texture more plastic in appearance. It is beautifully uniform in character. On one end of this specimen, where a piece had been nicked and then broken off by a sharp blow, the absence of all fibrous appearance, and the granular texture and magnificently fine, regular grain are very marked, and indicate that the material is entitled to its established position as the purest

Fig. 6.



metal known in the market. The specimens themselves furnish almost as valuable information, after test, as the diagrams contain, and should always be carefully inspected with a view to securing additional or corroborative information.

Fig. 5.

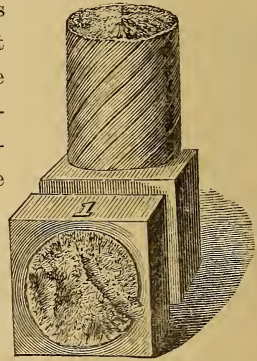


Fig. 5 is a sketch of specimen No. 1, and shows its somewhat granular fracture, and the seamy structure produced by a defective method of working. Fig. 6, from specimen No. 16, more nearly resembles

* As on last page.

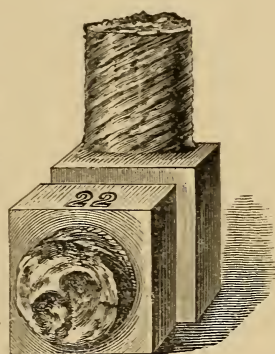
† From an article in the *Scientific American*, of January 17th, 1874, on “Testing the Quality of Iron, Steel and other Metals without Special Apparatus.”

that which gave the diagram marked 6. The metal is seen to be good, tough, and better in quality than No. 1, but it is even more seamy, and even less thoroughly worked, as is evidenced by the cracks extending around the neck, and by the irregularly distributed flaws seen on its end.

Fig. 7 exhibits the appearance of No.

Fig. 7.

22 after fracture, and shows, even more perfectly than the penciled record, the splendid character of the material. The surface of the neck was originally smoothly turned and polished, and carefully fitted to gauge. Under test it has become curiously altered, and has assumed a rough, striated appearance, while the helical markings extend completely around it. The end has the peculiar appearance which will be seen to be characteristic of tough and ductile metals, and the uniformly bright appearance of every particle in the fractured section shows how all held together up to the instant of rupture, and that fracture finally took place by true shearing. Rupture by torsion thus brings to light every defect and reveals every excellence in the specimen. Rupture by tension rarely reveals more than the mere strength of the material.



8.—LOW STEELS.—In Plate II, and above the curves just described, are a set obtained during experiments on “low steels,” produced by the Bessemer and Siemens-Martin processes. In general character, the curves are seen to resemble those of the standard irons, as illustrated by Nos. 1 and 6. The irons contain usually barely a trace of carbon. These steels contain from one-half to five-eighths of one per cent. The irons are made by a process which leaves them more or less injured by the presence of impurities, from which the utmost care can seldom free them. The steels are made from metal which has been molten and cast, a process which allows a far more complete separation of slag and oxides. The low steels, however, are liable to an objectionable amount of porosity, due to the liberation of gas while the molten mass is solidifying, whenever the spiegeleisen, employed as a conveyor of carbon, is not very rich in manganese. The results of these differences in constitution and treatment are readily seen by inspecting the curves. They show a stiffness equal to No. 6, and about the same degree of internal strain. They contain a sufficient number of the capillary channels,

produced by drawing down the pores while working the ingot into bar, to cause a lack of homogeneousness in structure, very similar to that produced in iron by cinder. They have a much higher elastic limit, and greater strength, and the softer grades have great ductility. In resilience, these softest steels excel all other metals, except the unusual example, No. 22, and are evidently the best materials that are now obtainable for all uses where a tough, strong, ductile metal is needed to sustain safely heavy shocks. A comparison of the diagrams of two competing metals may thus be made to indicate how far a difference in price should act as a bar to the use of the costlier one. For many purposes, a metal having double the resilience of another is worth more than double-price. For general purposes, a comparison of the resilience of the metals within the elastic limit is of supreme importance. No. 6 is seen to have more resilience within this limit than No. 1. and the steels far more than either; but No. 1 would take a set of considerable amount far within the true elastic limit, as indicated at *a*. The most valuable measure is obtained by determining the area intercepted between the "elastic line" and the perpendicular let fall from its upper end; this measures the resilience of elastic resistance, which is the really important quality.

No. 98 was cut from the head of an English Bessemer rail made from unmixed Cumberland ores. It contains nearly 0.4 per cent. carbon. It is quite homogeneous, has a limit of elasticity at 88 foot-pounds of torsional, or 26,400 pounds per square inch tensile stress, approaches its maximum of resistance rapidly, and, at 210°, the torsional moment becomes 225 foot-pounds, equivalent to 67,500 pounds per square inch tensile stress. It only breaks after a torsion of 283°, and with an ultimate elongation of 80 per cent, equivalent to a reduction of cross section to 0.556.

No. 76 is a Siemens-Martin steel made from mixed Lake Superior and Iron Mountain ores, and contained about the same amount of carbon as the preceding. It contains rather more phosphorus, which probably gives it its somewhat greater hardness, its higher limit of elasticity and its somewhat reduced ductility. Its elastic limit is found at 104 foot-pounds of torsion, or 31,200 pounds tensile resistance, and its ultimate strength is almost precisely that of the preceding specimen. Its elongation is 0.66 maximum. Unless more seriously affected by extreme cold than No. 98, it would be preferred for rails, and, perhaps, for most purposes.

No. 67 is a somewhat "higher" steel, made by the same process. It is less homogeneous than the two just examined, has greater strength and a higher elastic limit, but less ductility. Its resilience is very nearly the

same as that of Nos. 98 and 76. The elasticity of all of these steels seems very exactly the same. The ductility of No. 67 is measured by 0.40 elongation. At *d*, is seen another illustration of elevation of the elastic limit. The piece was left twenty-four hours under maximum stress. The torsional force was then removed entirely. On renewing it, as is seen, the resistance of the specimen was found increased in a marked degree.

No. 69 is an American Bessemer steel, containing not far from 0.5 per cent. carbon. The same effect is seen here that was before noted, an increase of hardness, a higher elastic limit, and greater strength, obtained however, by some sacrifice of both ductility and resilience. The elastic limit is approached at 130 foot-pounds of torsional moment, or 39,000 pounds tensile, and the maximum is 280 foot-pounds of moment and 84,000 pounds tensile resistance at 133°. Its maximum angle of torsion is 150°, its elongation 0.24.

No. 85 is a singular illustration of the effects of what is probably a peculiar modification of internal strain. It seems to have no characteristics in common with any other metal examined. Its diagram would seem to show a perfect homogeneousness as to strain, and a remarkable deficiency of homogeneity in structure. It begins to exhibit the indications of an elastic limit at *a*, under a torsional moment of 110 foot-pounds, or an apparent tensile stress of 33,000 pounds per square inch, and then rises at once by a beautifully regular curve, to very nearly its maximum at 16°, and 176 foot-pounds. The maximum is finally reached at 130°, and thence the line slowly falls until fracture takes place at 195°. The maximum resistance seems* to be very exactly 60,000 pounds to the square inch. Its maximum elongation for exterior fibres is about 0.23. The resilience taken at the elastic limit is far higher than with common iron, and it is seen that this metal, in many respects, may compete with steel. Its elasticity is seen to remain constant wherever taken. This singular specimen was a piece of "cold rolled" iron. It is probably really far from homogeneous as to strain, but its artificially produced strains are symmetrically distributed about its axis, and being rendered perfectly uniform throughout each of the concentric cylinders into which it may be conceived to be divided, the effect, so far as this test, or so far as its application as shafting, for example, is concerned, is that of perfect homogeneousness. The apparently great deficiency of homogeneousness in structure is readily explained by an examination of the pieces after

* With an exceptional case, of which this is an example, the scale for tension is incorrect. The tensile strength is probably higher than here given.

fracture ; they are fibrous, and have a grain as thread-like as oak ; their condition is precisely what is shown by the diagram, and the metal itself is as anomalous as its curve.

8. TOOL STEELS.—The “tool steels” differ chemically from the “low steels” in containing a higher percentage of carbon, and usually, in being very nearly, if not absolutely, free from all injurious elements. They are made in crucibles by melting down the blister steels which are the crude product of the process of cementation, or sometimes, by melting a charge composed of selected iron, a small proportion of manganese bearing alloy and the proper amount of carbon. Containing a higher proportion of carbon than the preceding class of metals, it is comparatively easy to secure homogeneousness by the introduction of manganese, and by the same means, to eliminate very perfectly the evil effects of any small proportion of sulphur that may be present. Their comparatively large admixture of carbon makes them harder, and reduces their ductility, and since the reduction of ductility occurs to a greater degree than the increase of strength, the effect is also to reduce their resilience. The working of these metals is more thorough than is that of the less valuable steels, or of iron. They are cast in comparatively small ingots, and are frequently drawn down under the hammer, instead of in the rolls, and are thus more completely freed from that form of irregularity in structure noticed so invariably in steels otherwise treated. The effect of increasing the proportion of carbon, is to confer upon iron the property of hardening, when heated to a high temperature, and suddenly cooling, and the invaluable property of “taking a temper,” *i.e.*, of assuming, under proper treatment, any desired degree of hardness. The hard steels are, however, comparatively brittle, the hardening being secured at the expense of ductility. The effect produced upon the tenacity of unhardened steel, by increasing proportions of carbon is somewhat variable, since it is influenced greatly by the presence of other elements. For good steels unhardened, the writer has been accustomed to estimate tenacity by the following formula, which is approximately accurate, and may be often found useful

$$T = 60,000 + 70,000 C.$$

in which T represents the tenacity in pounds per square inch, and C is the percentage of carbon contained in the metal. This subject will be considered at greater length after a series of experiments have been made to obtain more exact determinations.

Referring to Plate II, a set of diagrams will be found, having their

origin at 180°, which are *fac similes* of those automatically produced during experiments upon various kinds of tool steels.

No. 58 is an English metal, known in the market as "German crucible steel." It is remarkable as having a condition of internal strain which has distorted its diagram to such an extent as to completely hide the usual indication of the elastic limit. A careful inspection shows what may be taken for this point at about $14\frac{1}{2}^\circ$ of torsion, when the twisting moment was about 120 foot-pounds, and the tensile resistance 36,000 pounds per square inch. The metal is homogeneous in structure, has an ultimate resistance of 302 foot-pounds of moment, or 90,600 pounds per square inch tensile resistance. Its resilience is evidently inferior to that of the softer metals, and also less than the next higher and better grades. This metal contains about 0.60 to 0.65 per cent. carbon. Its elongation amounts to 0.045.

No. 53 is an English "double shear steel," of evidently very excellent structure, but less strong and less resilient than the preceding. Its exterior fibres are drawn out three per cent.

Nos. 41 and 61 are two specimens of one of the best English tool steels in our market. The first was tested as cut from the bar, but the second was carefully annealed before the experiment. In this instance, annealing has caused a slight loss of resilience as well as a decided loss of strength. In No. 41, the limit of elasticity can hardly be detected, but seems to be at about the same point as in No. 61, at near 130 foot-pounds moment and 39,000 pounds tension. The ultimate strength is nearly 119,000 pounds per square inch. The proportion of carbon is very closely 1 per cent. Its section would reduce by tension, 0.05.

No. 70 is an American "spring steel," rather hard, but as shown by its considerable resilience, of excellent quality, resembling remarkably the tool steel No. 41. It differs from the latter, apparently by its much higher elastic limit. It is possible that this may have been caused by more rapidly cooling after leaving the rolls in which it was last worked. It is evident that, for exact comparison, all specimens should be either equally well annealed or should be tempered in a precisely similar manner, and to the same degree.

Nos. 71 and 82 are American tool steels, containing about 1.15 of carbon. The former is notable as having an elastic limit at 69,000 pounds, and a probable deficiency of manganese, producing the usual indication of heterogeneous structure. Both of these steels lack resilience, and are less well adapted for tools like cold chisels, rock drills,

and others which are subjected to blows, than for machine tools. They have a maximum elongation, respectively, of but 0.013 and 0.03.

Interesting and instructive as the study of these curves may be made, the information obtained from them is supplemented, in a most valuable manner, by that obtained by the inspection of the fractured specimens, upon which the peculiar action of a torsional strain has produced an effect in revealing the structure and quality of the metal that could be obtained in no other way.

Fig. 8 represents the appearance of No. 68, and Fig. 9 that of No.

Fig. 8.

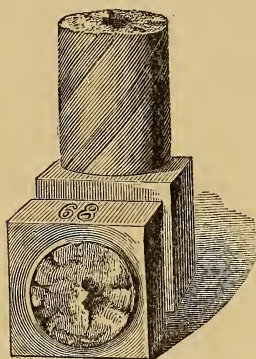
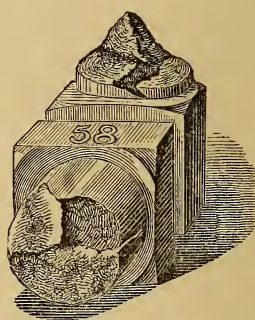
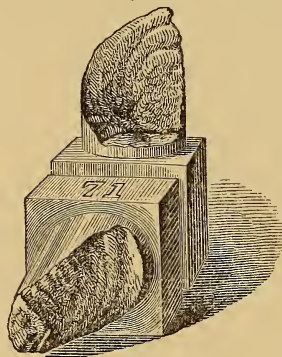


Fig. 9.



58, while the peculiarities of the finest tool steels are seen in No. 71, as

Fig. 10.



shown in Fig. 10. The smooth exterior of No. 68, which is a companion specimen to that giving diagram 69, and its bright and characteristic fracture, resembling that of No. 22 somewhat, together indicate its nature perfectly, the first feature proving its strength and uniformity of structure, and the second showing, even to the inexperienced eye, its toughness. This is a representative specimen of low steels. No. 58 is seen to have retained, even more than No. 68, its original smoothly polished surface. Its fracture is

less waxy, and much more irregular and sharply angular. The crack running down the side of the neck shows its relationship to the shear steels which much oftener exhibit this effect of strain, in consequence of their lamellar character. No. 58 is evidently intermediate in its character between the soft steels, like No. 68, and the tool steels which are

represented by No. 71, Fig. 10. In this test-piece, the fracture is ragged and splintery, and the separated surfaces have a beautifully fine, even grain, which proves the excellence of the material. The surface which was turned and polished in bringing the metal to size remains as perfect as before the specimen was broken. By an inspection of the broken test pieces in this manner, the grade of the steel, and such properties also as are not revealed by an examination of the diagram of strain, are very exactly ascertained by a novice, and to the practical eye, the slightest possible variations of character are readily distinguishable.

9. CAST-IRON.—The diagrams of strain having their commencement at 100° , have been obtained from cast-iron and from malleableized cast-iron.

Nos. 23 and 24 are those given by a good dark grey foundry iron from Pennsylvania. No. 25 represents the curve of light grey scrap, and No. 30 is from a very fine white Lake Superior charcoal iron. The latter is seen to be exceedingly hard and rigid, the resistance of the piece rising very precisely in proportion to the angle of torsion until it snaps at last under a moment of over 200 foot-pounds, equivalent to a tension of 60,000 pounds per square inch, and with a maximum elongation of one-tenth of one per cent. This is a most extraordinary resistance, but it is evident that, notwithstanding its immense strength, this material would be valueless for ordinary purposes in consequence of its excessive brittleness. When the torsional effort had reached about one-half its maximum amount the piece was released. The pencil retreated along a nearly vertical line e , which it again traversed as the strain was gradually renewed. Here as in many other cases, where a similar experiment was made, evidence is given of the truth of the statement originally made by Hodgkinson,* that every load produces a set. As will be shown, subsequently, however, it is not true in perfectly homogeneous bodies free from strain, and within their elastic limit. The light grey iron has a limit of elasticity at near one-half the maximum reached by the white iron, without any sign of reaching the limit of its elasticity. The grey has more ductility than the white iron, but has only about two-thirds the resilience of the latter. The dark grey irons are evidently better than either of the lighter grades, except in power of carrying an absolutely static load. The actual stretch of the outer surface particles is very nearly the same in all three. They are excellent specimens of their class, and considerably better than ordinary irons.

* Reports of British Association; also Civil Engineer and Architects' Journal.

No. 37 is a "malleableized cast-iron," made from the extraordinary metal illustrated in No. 30. The process of malleableizing consists in decarbonization by heating the casting made from good white iron, in contact with iron oxide or other decarbonizing material. Without removing any other constituent than the carbon, it produces a crude steel or an impure wrought-iron. When performed in the usual manner, melting the cast-iron in a cupola in contact with the fuel, and with some flux, and then carrying the process of malleableizing to the usual extent, a metal is obtained such as is illustrated by the diagram marked 37. It retains the strength of the cast-iron, and acquires some ductility.

No. 30 yielded 7° before fracture, while No. 37, vastly more ductile and resilient, only broke after a torsion of 39° , and a maximum elongation of 2 per cent. Taking the precaution to melt the iron in an "air furnace"—a form of "reverberatory"—and conducting the process of malleableizing more carefully, a still more valuable material was obtained.

No. 35 represents this iron. Its resemblance to wrought-iron, both in appearance of fracture and in its strength and ductility, are greatly increased. It has a high limit of elasticity—over 20,000 pounds per square inch—and such ductility that it only breaks after a torsion of nearly 168° , and an elongation of "fibre" of 0.35. It is not very homogeneous, but it is as strong, and almost as tough, as a good wrought-iron. This material has especial value for many purposes, because of the facility with which awkwardly shaped pieces can be made of it. In many cases, it will prove as good as wrought-iron and far cheaper.

Fig. 11.

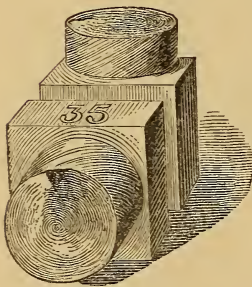
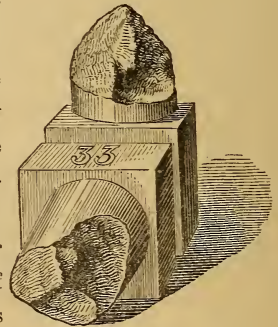


Fig. 11 shows the appearance of this last specimen. Its resemblance to wrought iron is very noticeable. The lines running like the thread of a screw around the exterior of the neck, and the smooth even fracture in a plane precisely perpendicular to the axis, are the instructive features. Fig.

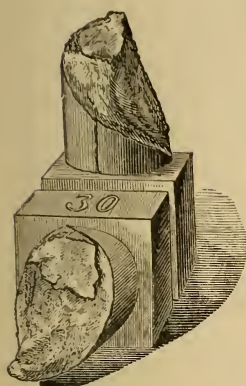
Fig. 12.



12, representing No. 33, is a specimen similar in character to No. 37. The comparative lack of ductility, its less regular structure, and its less perfect transformation are perfectly exhibited. Fig. 13 is an excellent

out of the white iron as cast and without malleableizing. Its surface where fractured, has the general appearance of broken tool steel. The color and texture of the metal are distinctive, however. It has none of the "steely grain." Fig. 14

Fig. 13.



represents the dark grey iron. Its color, its granular structure and coarse grain are markedly characteristic and no one can fail to perceive, in the specimen, the general character which is ex-

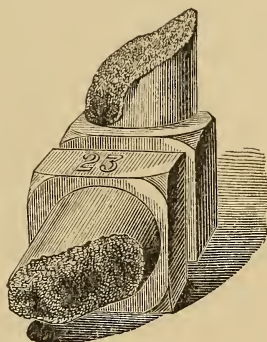
actly given by the autographic diagrams of the testing machine.

10. OTHER METALS.—The diagrams numbered 87, 88 and 89, are those of copper, tin and zinc. These specimens are all of cast metal, carefully selected under the direction of the writer and moulded and cast at the Stevens Institute of Technology. They exhibit neatly the wonderful superiority which the various kinds of iron and steel possess over the other useful metals. These metals all take a set under very small strains, pass their limits of elasticity at some indeterminable, but evidently low point, and possess very slight tenacity.

Zinc, No. 89, by the regularity of its curve shows a very uniform structure. It increases very gradually in resistance to torsion, until it reaches the angle 50° , at which point it has a moment of torsional resistance of 36 foot-pounds, and a maximum tenacity of about 10,800 pounds per square inch. It loses its power of resistance, after rupture commences, as regularly, but not as slowly, as it acquired it, and rupture becomes complete at 63° . Its resistance is exceedingly small, and it is evidently unfit to bear either static or dynamic force. Its stretching power has a maximum of 0.04.

Tin, No. 88, is equally remarkable for its exceedingly feeble resistance and its great ductility. The specimen was excellent, both in quality of metal and in closeness of structure, as was indicated by the clearness of the "tin cry" heard while undergoing the test and by the fine, smooth, clean fracture. The character of the curve is similar to that of zinc, but has far greater extent. Its elastic limit is quite indeterminable. The

Fig. 14.



outline of the diagram indicates very perfect homogeneousness. The maximum resistance to torsion is found at 240° , and under a stress of 19 foot-pounds. Its tenacity deduced from the diagram is, at most, but 5,700 pounds per square inch. Rupture occurs very gradually, and the piece separated entirely at 355° . Notwithstanding its great ductility, its low tenacity produces a low resilience, although in this quality it excels zinc, which latter metal had nearly double its strength. Its elongation by tension would have reduced its section to 0.6 of the original cross area, if that reduction were proportional to the ductility shown by the diagram.

Copper, No. 87, cast in green sand, like the zinc and tin just described, was found, on examination of the fracture, to differ from them in being exceedingly porous. The effect of this fault has been to weaken it seriously. Its curve closely resembles that of zinc, but is abruptly terminated by the piece suddenly breaking off at 46° . It reaches a maximum sooner than zinc, at 29° , and its greatest resistance to torsion is 36 foot-pounds, or to tension 10,800 pounds per square inch, precisely the same as zinc. Its ductility has a value of one and a half per cent. Its resilience is somewhat less than that of zinc. Its limit of elasticity is difficult to determine, but has been taken at $1\frac{1}{2}^{\circ}$ where the moment of resistance is 13 foot-pounds, equivalent very nearly to 3,900 pounds tenacity, per square inch.

No. 134 is the curve of cast copper, precisely similar to No. 87, but cast in a dry sand mould. The marked difference between these specimens is probably due, not only to the difference in degree of porosity which arises from the presence of vapor, which permeates the casting in one case, filling it with bubble holes, and which is almost unobservable in the last, but the slower cooling of the dry sand casting also probably produces its effect in strengthening the metal. This last specimen has a limit of elasticity at not far from $13\frac{3}{4}^{\circ}$, and under a torsional stress equivalent to a tension of 5,400 pounds per square inch. The maximum values of these quantities are found at 21° , and are 42 foot-pounds, and 12,600 pounds per square inch respectively. The resilience of the specimen is much greater than that of the preceding, and its maximum elongation is .026. Altogether, this is far better than the preceding, and it would seem that copper, and probably all its alloys, should, when possible, be cast in dry sand, to secure density and strength.

No. 141 is a piece of forged copper, hammered into a one-inch square bar, from a piece originally $3\frac{1}{2}$ inches wide and $\frac{3}{4}$ inch thick. The most striking property noticed is its immense ductility, far exceeding that of any other piece of metal yet tested, and, in amount, many times as great

as the cast metal. Its limit of elasticity is reached very quickly, although it is impossible to say precisely where it occurs. Comparing its "elastic line" with the initial portion of the curve, it is seen that the slightest force produces a set which is proportionally large as compared with the sets of other metals. The curve rises very regularly and gradually to a maximum, which is only attained, however, after a total angle of tension of 450° , and which measures 96 foot-pounds moment, or 28,800 pounds per square inch. Rupture is finally obtained after a torsion of 543° . The maximum elongation is 210 per cent., the most elongated lines of particles being finally left of 3.100 times their original length. Had this change of form occurred by reduction of section, the fractured area would have been but .323 the area of original section. The resilience of this piece of metal is evidently insignificant within the limit of which it would be seriously distorted by a blow, but is quite large in amount where resistance extends to the point of rupture. This is perfectly consonant with that knowledge of the material which every mechanic derives from experience with it. Here, however, we have a complete account of its properties, written out by the material itself with definite and accurate measures.

11. GENERAL CONCLUSIONS.—These plates, exhibiting the diagrams, which are the autographs of all the useful metals, illustrate sufficiently well the remarkable fullness and accuracy with which their properties may be graphically represented, and the convenience with which they may be studied, with the aid of so simple a recording machine. A comparison of results deduced as shown, with those obtained, so far as they can be obtained at all, the usual method of simply pulling the specimens asunder, and trusting to, sometimes, unskillful hands and an untrained observer, for the adjustment of weights and the registry of results, will indicate the close approximation of this method in even ascertaining the behavior of the metal in tension. On examining the beautifully plotted curves given by Knut Styffe, as representing the results of the experiments, made by him and by his colleagues, with a tensile machine, no one can fail to be struck with the similarity of those diagrams to the curves here produced automatically, and it will be readily believed that not only must there be very perfect correspondence of results where the two methods are carefully compared, but, also, that any theory of rupture must be defective which does not apply to both cases. The equations of the curves here given and those of the curves obtained by Styffe must have forms as similar as the curves themselves.

The constant ratio here assumed between the torsional resistance and

the tensile strength of the metals, and of homogeneous materials generally is based upon a comparison of the results here given with those obtained from the irons by tensile test, by the writer, and is confirmed by a compilation of results given by other experiments on the same brands.

12. TESTING WITHIN THE LIMIT OF ELASTICITY.—In determining the value of materials of construction, it is usually more necessary to determine the position of the limit of elasticity and the behavior of the metal within that limit than to ascertain ultimate strength or except, perhaps, for machinery, even the resilience. It is becoming well recognized by engineers who are known to stand highest in the profession, that it should be possible to test every piece of material which goes into an important structure and *to then use it* with confidence that it has been absolutely proven to be capable of carrying its load with a sufficient and known margin of safety. It has quite recently become a common practice to test rods to a limit of strain determined by specification, and to compel their rejection when found to take a considerable permanent set under that strain. The method here described allows of this practice with perfect safety. The limit of elasticity occurs within the first two or three degrees, and, as seen, the specimen may be twisted a hundred, or even sometimes two hundred times as far without even reaching its maximum of resistance, and often far more than this before actual fracture commences. It is perfectly safe, therefore, to test, for example, a bridge rod up to the elastic limit, and then to place the rod in the structure, with a certainty that its capacity for bearing strain without injury has been determined and that formerly existing internal strain has been relieved. The autographic record of the test would be filed away, and could, at any time, be produced in court and submitted as evidence—like the “indicator card” of a steam engine—should any question arise as to the liability of the builder for any subsequent accident, or as to the good faith displayed in fulfilling the terms of his contract. A special machine has been designed for this case.

13. The above will be sufficient to show the use and the value of this method. In the course of experiment upon a large number of specimens of all kinds of useful metals and of alloys, a number of interesting and instructive researches have been pursued, and some unexpected discoveries have been made. Before taking up the theory of rupture, the construction of equations, and the determination of their constants, a section will be devoted to an account of these investigations.

AUTO WOODS

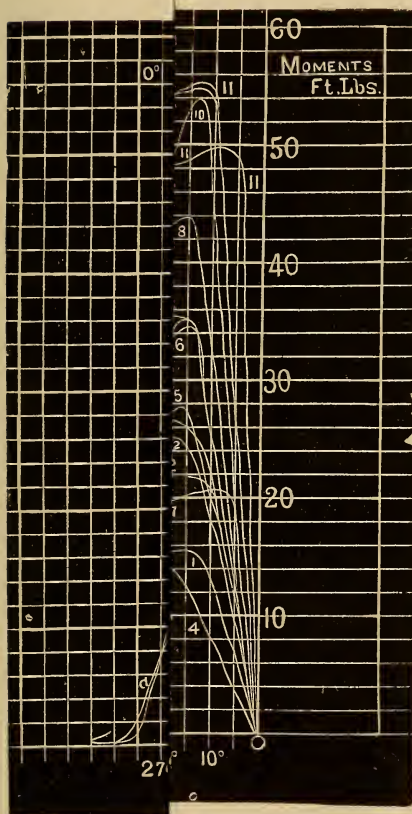
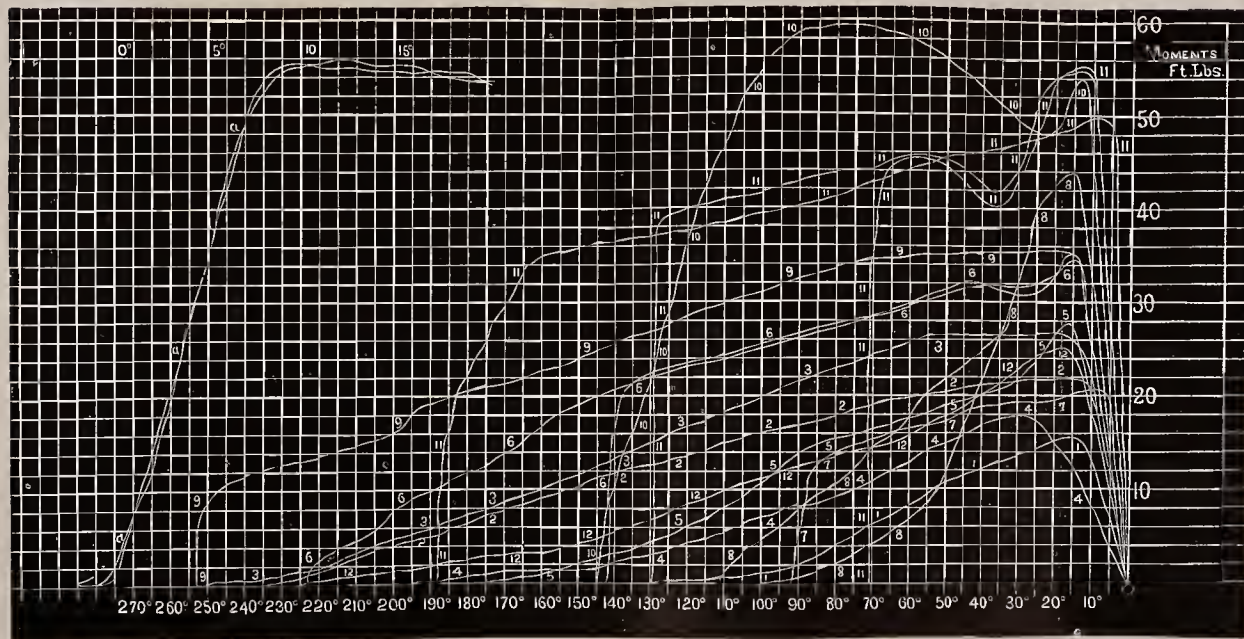


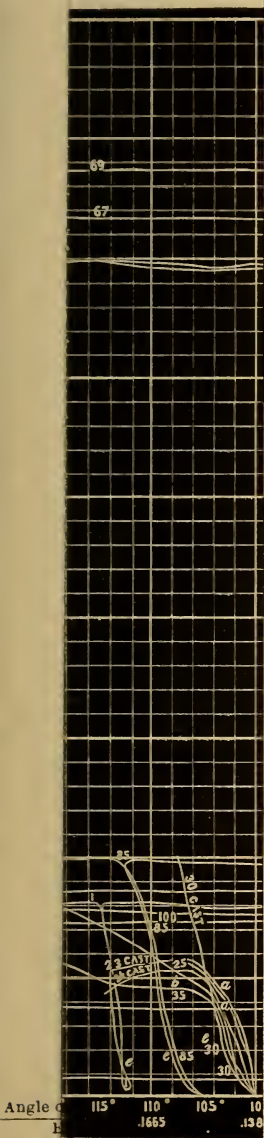
PLATE I.
AUTOGRAPHIC STRAIN-DIAGRAMS OF WOODS
PRODUCED BY THE
TESTING MACHINE OF PROFESSOR R. H. THURSTON.





R A M S

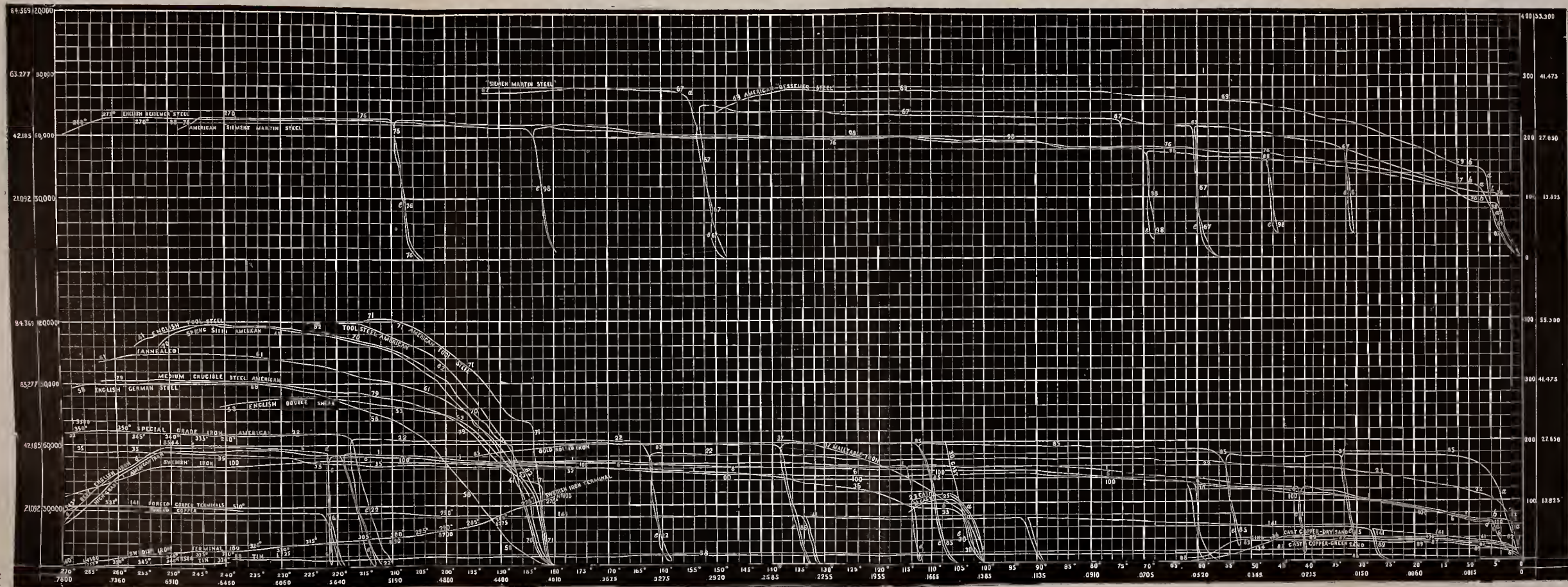
. H. THURS

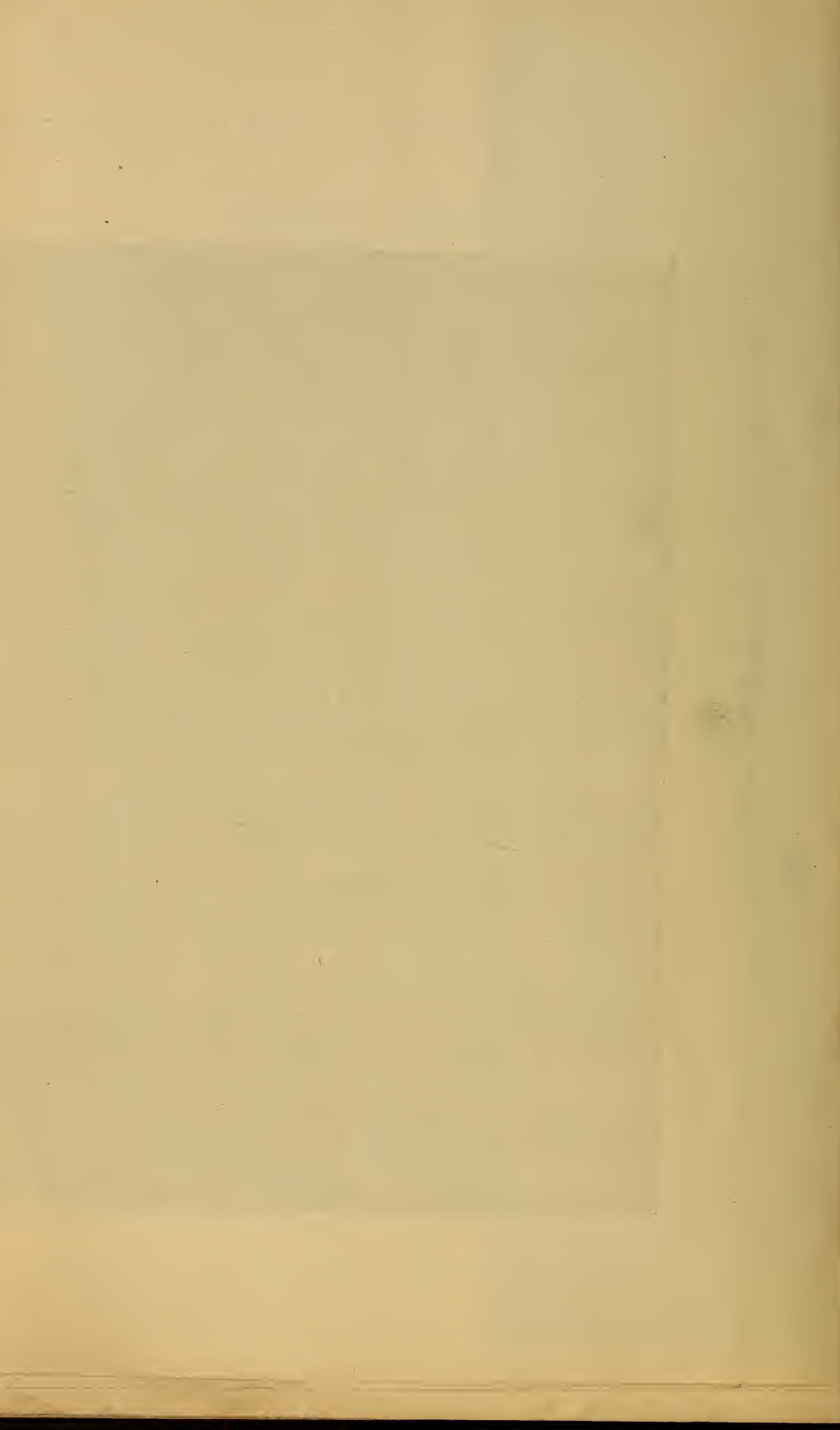


TESTING MACHINE OF PROFESSOR R. H. THURSTON.

| Kilogrammes per square Millimetre. | Pounds per square Inch of Section. |
|--|--|
|--|--|

| Foot-Pounds. | Kilogrammetres. |
|--------------|-----------------|
| 100 | 13.7 |
| 200 | 27.4 |
| 300 | 41.1 |
| 400 | 54.8 |
| 500 | 68.5 |
| 600 | 82.2 |
| 700 | 95.9 |
| 800 | 109.6 |
| 900 | 123.3 |
| 1000 | 137.0 |
| 1100 | 150.7 |
| 1200 | 164.4 |
| 1300 | 178.1 |
| 1400 | 191.8 |
| 1500 | 205.5 |
| 1600 | 219.2 |
| 1700 | 232.9 |
| 1800 | 246.6 |
| 1900 | 260.3 |
| 2000 | 274.0 |
| 2100 | 287.7 |
| 2200 | 301.4 |
| 2300 | 315.1 |
| 2400 | 328.8 |
| 2500 | 342.5 |
| 2600 | 356.2 |
| 2700 | 369.9 |
| 2800 | 383.6 |
| 2900 | 397.3 |
| 3000 | 411.0 |
| 3100 | 424.7 |
| 3200 | 438.4 |
| 3300 | 452.1 |
| 3400 | 465.8 |
| 3500 | 479.5 |
| 3600 | 493.2 |
| 3700 | 506.9 |
| 3800 | 520.6 |
| 3900 | 534.3 |
| 4000 | 548.0 |
| 4100 | 561.7 |
| 4200 | 575.4 |
| 4300 | 589.1 |
| 4400 | 602.8 |
| 4500 | 616.5 |
| 4600 | 630.2 |
| 4700 | 643.9 |
| 4800 | 657.6 |
| 4900 | 671.3 |
| 5000 | 685.0 |
| 5100 | 698.7 |
| 5200 | 712.4 |
| 5300 | 726.1 |
| 5400 | 739.8 |
| 5500 | 753.5 |
| 5600 | 767.2 |
| 5700 | 780.9 |
| 5800 | 794.6 |
| 5900 | 808.3 |
| 6000 | 822.0 |
| 6100 | 835.7 |
| 6200 | 849.4 |
| 6300 | 863.1 |
| 6400 | 876.8 |
| 6500 | 890.5 |
| 6600 | 904.2 |
| 6700 | 917.9 |
| 6800 | 931.6 |
| 6900 | 945.3 |
| 7000 | 959.0 |
| 7100 | 972.7 |
| 7200 | 986.4 |
| 7300 | 1000.1 |
| 7400 | 1013.8 |
| 7500 | 1027.5 |
| 7600 | 1041.2 |
| 7700 | 1054.9 |
| 7800 | 1068.6 |
| 7900 | 1082.3 |
| 8000 | 1096.0 |
| 8100 | 1109.7 |
| 8200 | 1123.4 |
| 8300 | 1137.1 |
| 8400 | 1150.8 |
| 8500 | 1164.5 |
| 8600 | 1178.2 |
| 8700 | 1191.9 |
| 8800 | 1205.6 |
| 8900 | 1219.3 |
| 9000 | 1233.0 |
| 9100 | 1246.7 |
| 9200 | 1260.4 |
| 9300 | 1274.1 |
| 9400 | 1287.8 |
| 9500 | 1301.5 |
| 9600 | 1315.2 |
| 9700 | 1328.9 |
| 9800 | 1342.6 |
| 9900 | 1356.3 |
| 10000 | 1370.0 |







LIBRARY OF CONGRESS



0 028 116 609 8

LIBRARY OF CONGRESS



0 028 116 609 8



Hollinger Corp.

pH 8.5